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INFLUENCE OF THICKNESS FLUCTUATIONS ON EXCHANGE COUPLING IN Fe/Cr/Fe STRUCTURES

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1. Introduction

Realizing the ultimate limits in fabrication requires the controlled placement of material at the single atomic layer limit. This precision is required for both semiconductor and magnetic devices, the two largest industries racing towards the *Ultimate Limits* in fabrication. In this report we summarize results on the effects of thickness fluctuations on the exchange coupling in Fe/Cr/Fe trilayer structures [1]. This work demonstrates the importance of controlling thin film thickness at the single atomic layer level in magnetic systems.

An increasingly important of area of magnetic research has been in the exchange coupling between two magnetic layers separated by a nonmagnetic spacer layer. This has resulted from the potential application of such devices to magnetic sensor technology based on the "giant magnetoresistance" or "spin valve effect" seen in coupled layers [2,3]. Central to understanding of the exchange coupling of such magnetic multilayer systems has been the observation of multiple oscillatory periods in the exchange coupling and the correlation of these periods with the spacer layer electronic structure [4,5]. In measurements of Fe/Cr multilayers, the exchange coupling of two Fe layers was discovered to oscillate between ferromagnetic and antiferromagnetic coupling as a function of Cr thickness with a period of ~12 layers [6]. In subsequent measurements of Fe/Cr/Fe(100) trilayer structures, an additional short period oscillation of approximately two atomic layers was observed and could even be dominant depending on sample preparation conditions [7]. The critical parameter was the temperature of the Fe(100) substrate during Cr evaporation. In this article we show that the temperature and thickness dependence of Cr growth leads to thickness fluctuations in the Cr interlayer which have profound effects on the observed exchange coupling in Fe/Cr/Fe trilayer structures. The thickness fluctuations are measured with Scanning Tunneling Microscopy (STM) and the exchange coupling is observed by magnetic imaging using Scanning Electron Microscopy with Polarization Analysis (SEMPA).

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2. SEMPA Measurements of Magnetic Coupling

SEMPA is a relatively new technique for obtaining images of magnetic microstructure. It relies on measuring the spin polarization of secondary electrons which are generated in a scanning electron microscope (SEM). The polarization of the emitted secondary electrons is characteristic of the surface magnetization of the solid, thus yielding a magnetic image as the electron beam is rastered in the SEM [8,9].

SEMPA measurements were made on Fe/Cr/Fe structures described previously [7] in which the Cr interlayer was deposited in a "wedge-shaped" layer of linearly increasing thickness on the nearly perfect single crystal Fe whisker substrate held at a designated temperature. A thin film of Fe, five to ten monolayers thick, was then evaporated on the Cr at room temperature. The wedge geometry has the advantage that it allows simultaneous measurements of many different thicknesses. The wedge thickness is calibrated with scanning RHEED measurements, which give a precise measure of the Cr thickness, to ± 0.1 monolayer, as a function of position along the wedge. Figure 1 shows SEMPA magnetization images of the Fe overlayer of a Fe/Cr/Fe(100) sandwich coupled through the Cr spacer layers grown at Fe substrate temperatures of 30°C, 200°C, and 350°C. The Cr spacer layer is wedge-shaped, increasing in thickness from 0 to 40 monolayers from the left to the right of the images in Fig. 1. The magnetization of the Fe overlayer is parallel (ferromagnetically coupled) to the substrate magnetization in the white regions and antiparallel (antiferromagnetically coupled) in the black regions. As the Cr interlayer thickness changes, the coupling oscillates with two distinct periods. Which of the two periods of oscillation is dominant depends on the growth temperature of the Cr spacer layer, as seen in Figs. 1(a-c). In addition, in Fig. 1(b) the short period oscillation is initially observed, but then dies out leaving only the long period oscillation. Therefore the period of oscillation is both growth temperature dependent and thickness dependent.

3. STM Measurements of Cr Growth

STM measurements were used to measure the quality of film growth. Detailed measurements were made to characterize the starting surface of the Fe(100) whisker, and to gain a fundamental understanding of nucleation and growth processes [10]. STM measurements of the film growth were made at room temperature after quenching a film which was grown at a designated temperature. The resulting surface morphology corresponds to a "snap-shot" of the surface at the time the growth was interrupted.

Figure 2 shows the surface morphology Cr films, of approximately five monolayer thick, grown on a Fe(100) whisker at 50°C, 215°C, and 300°C. A large variation in roughness is observed depending on growth temperature, similar to the large variation observed in the exchange coupling in Fig. 1. At the lowest growth temperature, corresponding to Fig. 2(a), the Cr surface layers from the 3rd to 7th are exposed. The distribution of each thickness exposed is approximately a gaussian distribution with an rms deviation, σ, of 0.86 monolayers (0.124 nm).

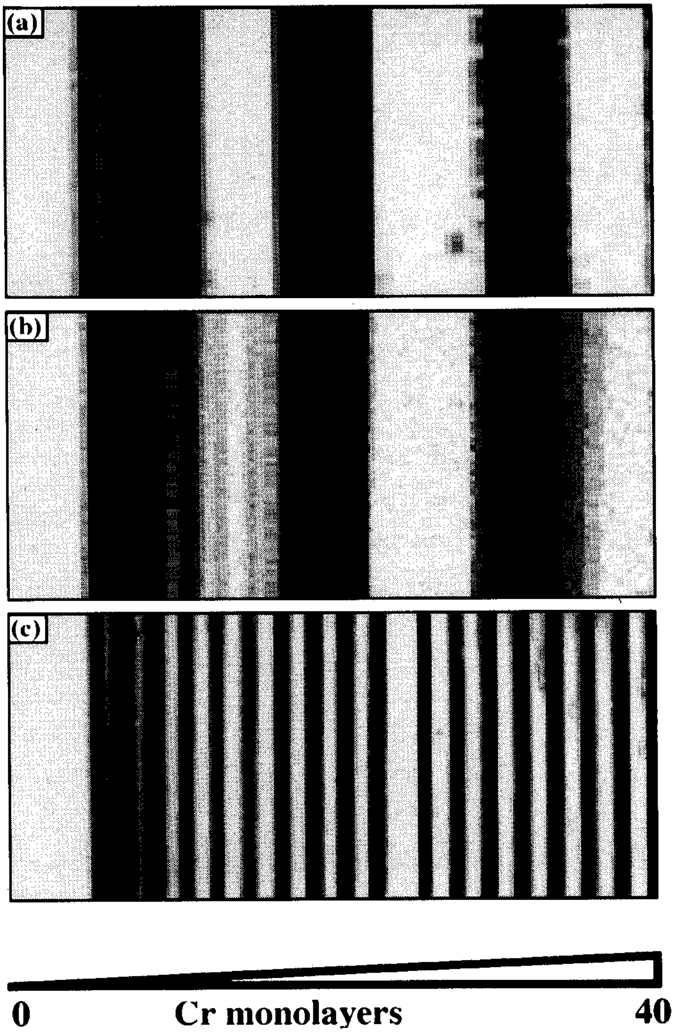

Figure 1. SEMPA magnetization images of the Fe overlayer coupled through Cr spacer layers grown at Fe substrate temperatures of a) 30°C, b) 200°C, and c) 350°C respectively. The Cr spacer layer increases in thickness from 0 to 40 monolayers, as indicated, from the left to the right of the images. The magnetization of the Fe overlayer is parallel (ferromagnetically coupled) to the substrate in the white regions and antiparallel (antiferromagnetically coupled) in the black regions.

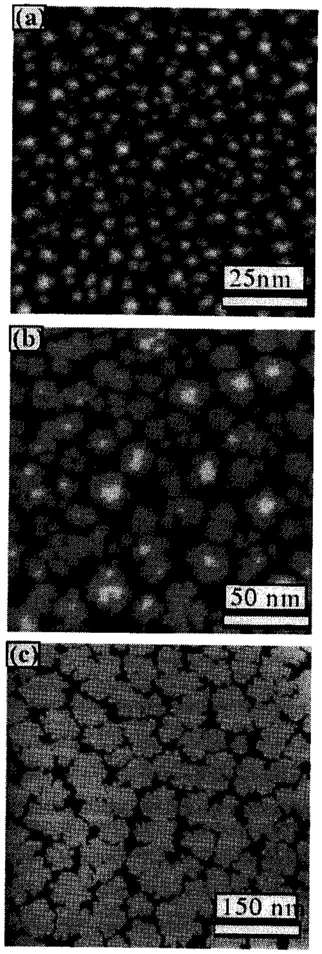

Figure 2. STM images of ~5 monolayers of Cr grown on a Fe(100) whisker held at temperatures of a) 50°C, b) 215°C, and c) 300°C. The images are 100x100 nm, 200x200 nm, and 600x600 nm, respectively.

At higher growth temperature the deposited atoms have a greater diffusion constant which favors growth over nucleation, leading to smoother films. In Fig. 2(c) we observe that growth at 300°C yields the ideal layer-by-layer growth where one atomic layer is completed before another layer begins to grow. At intermediate growth temperatures, as shown in Fig. 2(b), one still observes a roughness intermediate between that of films grown at 50°C and 300°C. At temperatures such that diffusion is kinetically limited, such as in Figs. 2(a) and (b), the rms roughness, σ, scales with thickness t according to a power law [11],

$$\sigma = Ct^{\beta}, \tag{1}$$

where we have found that β=0.46 for the initial growth of Fe homoepitaxy of up to 20 monolayers.

The measured Cr surface distribution corresponds directly to a thickness fluctuation in the Cr film since the starting Fe whisker surface is extremely flat on the micron scale. It is this thickness fluctuation which is responsible for the variation in the observed exchange coupling in the Fe/Cr/Fe trilayer structures. Accounting for these fluctuations is described in the following section.

4. Modeling the Exchange Coupling

The exchange coupling $J_1(n)$ which leads to oscillations in the magnetization images of Fig. 1 can be modeled as the sum of two sine waves [1],

$$J_1(n) = \left(\frac{1}{nd}\right) A \sin\left(\frac{2\pi nd}{L_A} + \Phi_A\right) + \left(\frac{1}{n^2 d^2}\right) B \sin\left(\frac{2\pi nd}{L_B} + \Phi_B\right), \tag{2}$$

with periods L_A and L_B and phases Φ_A and Φ_B. The model interaction $J_1(n)$ is plotted as the solid circles in Fig. 3(c); it only has values at each thickness nd corresponding to a discrete number of monolayers n, each of thickness d. The strength of the effective interaction at any average thickness t is the sum of the interactions weighted by the fraction of the area, $P(t,n)$, at that average thickness having n monolayers,

$$J_1(t) = \sum_n P(t,n) J_1(n). \tag{3}$$

4.1 LAYER-BY-LAYER GROWTH AT 300-350°C

For the case of layer-by-layer growth the growth front consists of two layers where the fractional occupation of the surface layer increases linearly as we proceed from n to $n+1$ layers. In this case the function $P(t,n)$ is simple and corresponds to linearly interpolating the exchange interaction in Eq. (2) between integral layers. Equation (3) for this case is plotted as the solid line in the lower part of Fig. 3(c) normalized to the value $J_1(n)$ for n equal to one monolayer. The model magnetization profile, the dashed line in Fig. 3(c), is obtained by setting all positive values of the model coupling function $J_1(t)$ to the same positive magnetization value and all negative values to a negative magnetization of the same magnitude, plotted as M/M^*= +1 or -1, respectively. The parameters of Eq. (1) are varied to obtain the best fit to the experimental magnetization profile which is obtained from Fig. 1(c) and shown as the solid line in the upper part of Fig. 3(c). A best fit to the magnetization profile yields the periods L_A=2.105 ± 0.005 d and L_B=12.0 ± 1d, where d is the Fe lattice constant, 0.287 nm.

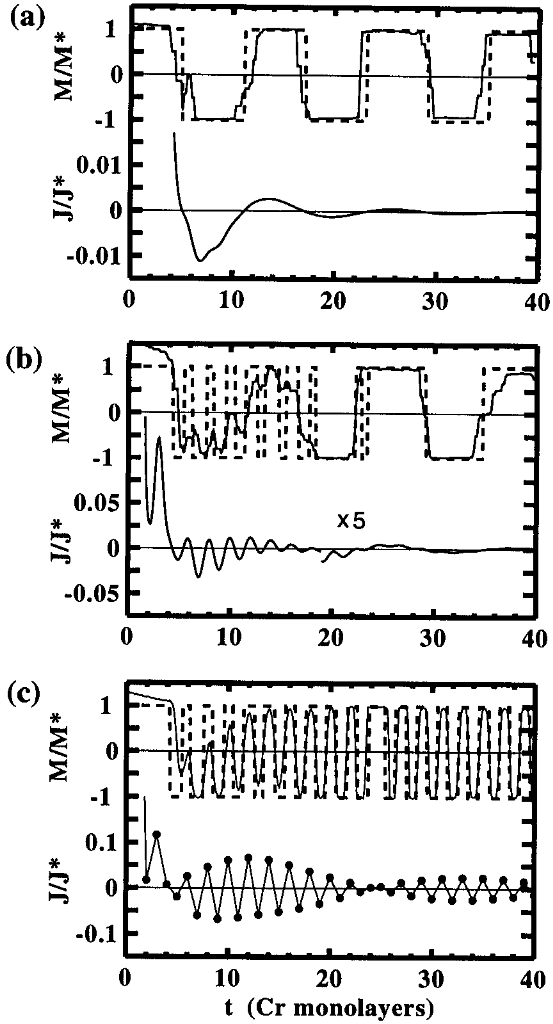

Figure 3. Profiles M/M^* of the normalized magnetization, M_y, from the SEMPA images of Fig. 1 are shown as solid lines in the upper parts of each panel corresponding to Cr growth at Fe substrate temperatures of a) 30°C, b) 200°C, and c) 350°C, respectively. The dashed line is the model magnetization calculated as described in the text. The solid line J/J^* in the lower part of each panel is the normalized interaction $J(t)$ at the average thickness t calculated from Eq. 3.

4.2 EFFECT OF ROUGHNESS ON COUPLING

We find that the magnetization profiles measured for rough Cr growth can be understood in terms of the exchange coupling $J_l(n)$ from Eq. (2) determined from the layer-by-layer growth if the thickness fluctuations obtained from the STM measurements are taken into account. For rough growth, even if the average thickness is exactly n monolayers, there may be thickness of n-2, n-1, n, n+1, and n+2 monolayers present in the growth front, as observed in Fig. 2. The exchange coupling $J_l(t)$ at each average thickness t is determined from Eq. (3) using the exchange coupling $J_l(n)$ from fitting the layer-by-layer growth (dots in Fig. 3(c)) weighted by the fraction of growth front of thickness nd contributing to the average thickness, as determined from the STM measurements. Figure 3(a) shows $J_l(t)$ and the resulting model magnetization profiles for the case of 50°C growth. The effect of the thickness fluctuations is seen to wipe out the short period oscillation in the exchange coupling leaving only the $12d$ period, in excellent agreement with the measured magnetization profile.

At the intermediate growth temperature the exchange interaction $J_l(t)$ initially shows short period oscillations which decay with thickness leaving only the long period, as observed in Fig. 3(b). The reason for this is that initially the thickness fluctuations are not great enough to average out the short period oscillations, but because the roughness scales with thickness, as given by Eq. (1), eventually the short period oscillations get damped out. In fact, eventually the long period oscillations decay in thicker wedges because of the roughness scaling in kinetically limited growth. The resulting model magnetization profile for this case is in excellent agreement with the measured magnetization profile.

In summary, we have showed how the periods of oscillations in the exchange coupling of Fe/Cr/Fe trilayers depend strongly on the roughness of the film growth at the single atomic layer level. A theoretical coupling function could be obtained by fitting the SEMPA magnetization profile in the case of layer-by-layer growth. Using this coupling function, and taking into account the thickness fluctuations in the Cr spacer layer measured by STM, we are able to understand the origins of the strikingly different SEMPA magnetization images of Fig. 1. Roughness due to both temperature effects and statistical scaling of roughness with thickness are necessary to understand the magnetization results.

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